SEDIMENT-TRANSPORT COMPETENCE OF RAIN-IMPACTED INTERRILL OVERLAND FLOW

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ABSTRACT

Laboratory experiments to determine the maximum size of sediment transported in shallow, rain-impacted flow were conducted in a recirculating flume 4·80 m long and 0·50 m wide. Rainfall intensities were varied between 51 and 138 mm h^{-1}, flow was introduced from a header tank into the flume at rates ranging from 0 to 0·64 1 s^{-1}, and experiments were conducted on gradients between 3·5 and 10°. The following equation was developed:

$$ML = (RE\,FE)^{1\cdot6363}$$

in which M is particle mass, L is distance moved in unit time (cm min^{-1}), RE is rainfall energy (J m^{-2} s^{-1}) and FE is flow energy (J m^{-2} s^{-1}). This equation can be used to predict sediment-transport competence of interrill overland flow. The equation is limited in its utility insofar as it has been developed using quartz grains and takes no account of variations in absorption of rain energy by natural ground surfaces. © 1998 John Wiley & Sons, Ltd.

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INTRODUCTION

The current conceptual model for soil erosion in interrill areas derives from the work of Meyer and Wischmeier (1969). These authors explicitly divided soil erosion into four subprocesses: (1) detachment by rainfall; (2) transport by rainfall; (3) detachment by overland flow; and (4) transport by overland flow. It has been shown that in interrill areas soil detachment is effected principally by rainfall (e.g. Borst and Woodburn, 1942; Ellison, 1945; Young and Wiersma, 1973) and that sediment transport is due mainly to overland flow (e.g. Young and Wiersma, 1973; Morgan, 1980). Consequently, under this model, interrill soil erosion is limited by whichever of these subprocesses operates at the lower rate.

The rate at which each subprocess operates is usually measured in terms of its capacity, i.e. the total amount of sediment affected by the subprocess. According to this scale of measurement, both theoretical and empirical research (Foster and Meyer, 1972, 1975; Meyer *et al*., 1975; Foster *et al*., 1977; Gilley *et al*., 1985) have suggested that sediment-transport capacity by overland flow is zero at the divide and increases with distance. Consequently this quantity acts as the limit to soil erosion close to the divide. Soil detachment by rainfall, on the other hand, is controlled by soil properties and rainfall-impact stress, and most authors assume that, under conditions of spatially uniform soil type and rainfall, the detachment rate is also uniform. An exception is Gilley *et al*. (1985) who argue that increasing depths of overland flow downslope afford increasing protection of the ground surface from raindrop impact, causing detachment to vary inversely with slope length. Either way, at some distance from the divide, the increasing transport rate exceeds the detachment rate so that the erosion rate is expected to become detachment-limited.

Recent empirical research has shown that, in supposedly detachment-limited portions of interrill areas, erosion rates are inconsistent with their being limited by the detachment rate. Abrahams *et al*. (1991) identified a downslope decrease in the rate of soil loss that could not be explained even by Gilley *et al*. (1985) proposition for a downslope decrease in the rate of detachment. Parsons *et al*. (1991) examined the size of sediment

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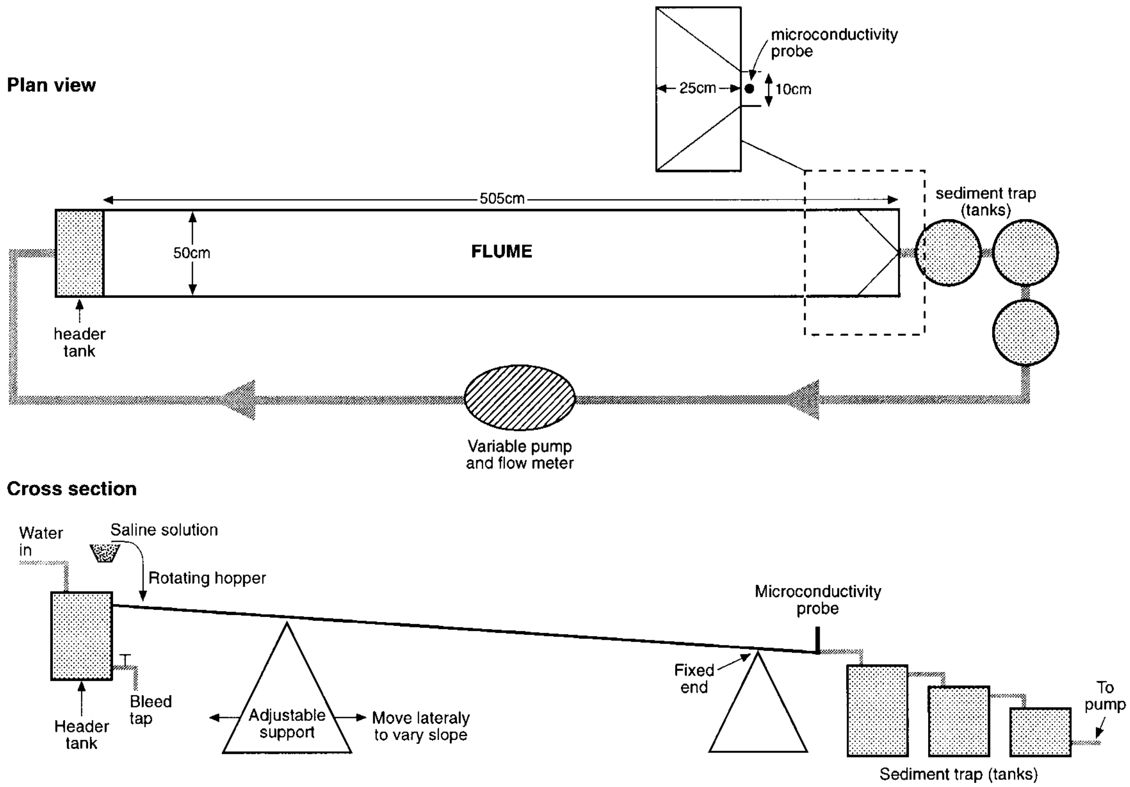

Figure 1. Design of recirculating flume used in the experiments

transported in interrill flow and found it to be smaller than that of raindrop-detached sediment. Furthermore, these authors found evidence to suggest that the rate of detachment was significantly greater than the rate of erosion, implying that erosion was limited by more than detachment alone. Parsons *et al.* (1992) showed that temporal variations in the rates of raindrop detachment and of interrill soil erosion exhibited poor correlation. Specifically, erosion rates were shown to be higher and/or increasing at times when detachment rates were lower and/or decreasing.

Two hypotheses have been put forward to explain these inconsistencies: (1) that the spatial variation in overland flow depth results in some detached sediment not being accessible for transport by overland flow; and (2) that the rate of sediment transport by overland flow needs to be measured in terms not only of its capacity but also of its competence, i.e. the maximum size of transportable sediment. Transport competence may be limiting even where transport capacity is not. This paper is concerned with the latter hypothesis.

Transport competence has been extensively studied in river flow. For such flow, competence is defined as the maximum size of particle that can be entrained by the flow from the bed. This size can be determined from the relationship developed by Shields (1936). Such an approach to determining competence of overland flow is inappropriate for several reasons (Guy *et al*,, 1992, p. 234), but particularly so for interrill overland flow where almost all the sediment is not entrained by the flow from the bed but supplied to the flow by raindrop detachment. Competence, therefore, must be defined in a different way – as the maximum size of particle that can be transported rather than entrained – and its determination must be obtained other than from the Shields relation. However, no means exists to predict competence under such conditions. Although laboratory experimental data exist to show that particles of a given size can be transported as bedload by flow at velocities equal to two-thirds of that required to entrain them (Sundborg, 1967), such data fail to take account of the role of rainfall in sediment transport by interrill flow. Furthermore, the term ‘transport’ is itself not straightforward. Individual particles are transported a finite distance before coming to rest. It has been argued that in interrill

flow these transport distances have a gamma distribution, with most sediment only travelling a short distance (Kirkby, 1991; Wainwright and Thornes, 1991; Parsons *et al*., 1993). Defining competence in terms of transport is, therefore, a complex issue.

The aim of this paper is to investigate the transport of particles in shallow, rain-impacted flow. Specifically the relationships among rainfall energy, flow energy and transport distance will be investigated. From this investigation a definition of competence for such flow in terms of transport distance (i.e. a finite distance in a finite time) will be presented. Using the data obtained from the investigation, a predictive equation for sediment-transport competence of rain-impacted shallow flow will be developed.

FLUME DESIGN AND EXPERIMENTAL METHODS

The study was undertaken using a recirculating flume (Figure 1), 0·50 m wide and 4·80 m long, bounded by 0·07 m high walls and tapering at its base to 0·10 m wide over 0·25 m. For the experiments reported here a fixed bed consisting of silica sand (Redhill 8/16, Hepworth Minerals & Chemicals Ltd), which had particle diameters between 1 and 2 mm and median particle diameter of 1·5 mm, was used. A 3 m reach, the top of which was situated 1·8 m from the top of the flume, was established, within which the experimental observations were conducted.

Flow was supplied to the flume from a header tank fed by water pumped from three 160 litre settling tanks which received water and sediment from the base of the flume. Flow from the header tank was controlled by means of a valve which diverted flow either to the header or back to the settling tanks. The gradient of the flume was varied by raising or lowering the header end of the flume. This system provided flow rates of 0 to 0·64 l s^{-1}, flow depths of 0 to 5 mm, operating on gradients between 0 and 10°. This range of experimental conditions provided flow energy *FE* varying from 0 to 1·193 J m^{-2} s^{-1}, where:

$$FE = \frac{\rho g Q s}{w} \tag{1}$$

in which ρ is the density of water, *g* is gravitational acceleration, *Q* is discharge, *s* is slope of the flume and *w* is width of the flume.

Artificial rainfall onto the flume was provided by a sprinkler system consisting of four nozzles (Lechler axial-flow-cone jet nozzles 483.427 and 460.848) located at the vertices of a 50 cm rectangular grid supported 4 m above the centre of the flume. The nozzles were supplied with water pumped from a storage tank at a nozzle pressure of 0·68 bar. Rain intensity was measured by six range gauges attached to the side of the flume and drop size was measured using the flour-pellet method, calibrated to actual raindrop size using Hudson's (1963) data. At the designed working pressure three of the nozzles (483.427) provided approximate individual rain intensities of 40 mm h^{-1} and one nozzle (460.848) provided 20 mm h^{-1}. Rainfall intensity was varied using four 3/4-inch electric globe solenoid valves which switched individual nozzles on or off. For the experiments reported here five rainfall intensities were used. These intensities were recorded as 51, 67, 106, 117 and 138 mm h^{-1}. The rain had a median drop diameter (D_{50}) varying between 1·0 mm (for 51 mm h^{-1}) and 3·4 mm (138 mm h^{-1}). The fall height, together with the exit velocity from the nozzles, means that almost all the raindrops will hit the flume at or within 10 per cent of their terminal velocity. Accordingly, the kinetic energy for the rainfall has been calculated on the basis of data for the terminal velocity of water drops in stagnant air given by Laws (1941) and Gunn and Kinzer (1949). For the five rainfall intensities these kinetic energies are 0·20, 0·24, 0·58, 0·65 and 0·85 J m^{-2} s^{-1}. Over the area of the flume the rainfall intensity had a coefficient of uniformity of 82·5 per cent. In addition to using these five rainfall intensities, experiments were conducted with zero rainfall.

Velocity of flow within the experimental reach was measured by introducing a sodium chloride solution 0·50 m down from the top of the flume and recording the variation in conductivity at the base of the flume. The variation in conductivity was logged by a computer. The centroid of the conductivity distribution curve was calculated, and the time taken for this point to pass the conductivity meter was used to calculate velocity. Velocity measurements were taken at the beginning and end of each experiment. Discharges were measured at

Table I. Median transport distances for experiment set I

Rainfall energy ($J m^{-2} s^{-1}$)	median transport distance (cm) for various flow energies ($J m^{-2} s^{-2}$)									
	0·05	0·1	0·15	0·2	0·25	0·3	0·35	0·4	0·45	0·5
A. Slope = 3·5°										
0·00	0·00	0·0	0·00	0·0	0·00	0·0	0·00	0·0	0·20	0·5
0·20	0·60	0·9	1·40	2·1	4·20	7·2	6·90	7·2	19·50	32·0
0·24	0·40	1·5	2·60	2·4	2·30	3·7	10·50	13·5	53·50	98·5
0·58	1·60	3·6	2·20	4·9	8·70	4·0	15·80	93·0	104·00	185·7
0·65			5·30	7·2	8·00	14·0	25·00	53·0	133·00	212·0
0·85			9·90	10·6	14·60	28·3	38·50	175·0	300·00	300·0
B. Slope = 5·5°										
0·00			0·00	0·0	0·20	1·3	2·50	2·9	5·20	
0·20			1·30	1·9	2·10	12·4	47·20	45·5	80·50	
0·24			1·20	1·6	2·60	16·5	22·50	20·9	123·50	
0·58			3·00	3·1	6·00	9·8	76·20	184·0	150·50	
0·65			5·20	5·5	9·40	19·4	35·00	99·0	300·00	
0·85			7·00	11·2	25·20	41·8	96·00	213·5	300·00	
C. Slope = 10°										
0·00		0·0	0·00	3·1	7·20	14·5				
0·20		0·5	0·70	6·1	18·90	182·0				
0·24		2·1	0·39	12·2	61·00	300·0				
0·58		6·6	6·30	12·2	19·00	300·0				
0·65		4·3	6·70	9·3	50·00	300·0				
0·85		7·5	13·30	17·7	27·50	300·0				

the flume outlet. Using these discharge measurements coupled with the rainfall data, the discharges at the midpoint of the experimental reach were calculated.

Once equilibrium rain-impacted flow conditions were established within the experimental reach, particles were introduced into the flow by placing them onto the bed at the top of the reach using tweezers. The particles consisted of spherical (according to Zingg's classification) quartz grains sorted into eight nominal 1 mm size classes (3,4,5 ... 10 mm) by measuring the intermediate axes of individual particles using callipers. The actual average grain intermediate axis size of each class was 2·88, 5·04, 5·25, 5·98, 7·38, 8·41, 9·5 and 10·63 mm. The particles were introduced into the flow at the top of the reach over a period of 1 min and the experiment was then run for a further 14 min, after which time the distances the particles had moved were measured. Thus, the distances measured represent particle movement over a time period of between 14 and 15 min.

Using this general methodology, two sets of experiments were conducted.

Experiment set I

The first set of experiments examined the relationship between rainfall energy, flow energy and transport distance using a single grain size. For each rain intensity (0–138 mm h^{-1}) 15 to 25 particles, taken from the 3 mm size class, were introduced into various flows with discharge varying between 0·1 and 0·21 s^{-1}. This procedure was conducted on slopes of 3·5, 5·5 and 10°. A total of 171 experiments was conducted in which the calculated rainfall kinetic energy varied between 0 and 0·85 J m^{-2} s^{-1} and flow energy varied between 0·05 and 0·50 J m^{-2} s^{-1}. Data obtained from this set of experiments are summarized in Table I.

Experiment set II

Based on the results of the first set of experiments, the second set of experiments was conducted in order to provide data for the derivation of a predictive equation for sediment-transport competence. These experiments differed from the first set in that grain size was also varied in order to assess the effect of grain size on transport competence. Experiments were conducted in which all the grain sizes (3–10 mm size classes) were subject to various combinations of rainfall intensity, flow velocity, flow depth and slope. In each experiment, 10 grains taken from a particular size class were introduced into the flow. In all, 226 experiments were conducted in which rainfall kinetic energy was varied between 0·20 and 0·85 J m^{-2} s^{-1} and flow energy was varied between 0·070 and 0·424 J m^{-2} s^{-1}. Data from this set of experiments are summarized in Table II.

Table II. Median transport distances for experiment set II

Slope (degrees)	Rainfall energy ($J m^{-2} s^{-1}$)	Flow energy ($J m^{-2} s^{-1}$)	median transport distance (cm) for various grain sizes (mm)							
			2·88	5·04	5·25	5·98	7·38	8·41	9·50	10·63
5·0	0·00	0·224	0·00	0·00	0·00	0·00	0·00	0·00	0·00	0·00
5·0	0·20	0·168	3·05	1·00	0·65	0·10	0·00	0·00	0·00	0·00
5·0	0·24	0·167	8·60	0·45	0·00	0·00	0·00	0·00	0·00	0·00
5·0	0·58	0·180	20·00	4·80	3·00	2·25	0·40	0·00	0·00	0·00
5·0	0·65	0·166	14·80	10·20	8·65	6·20	1·20	1·00	0·20	0·00
5·0	0·85	0·184	39·60	24·20	12·95	10·30	4·60	1·70	0·85	0·00
9·2	0·00	0·415	0·00	0·00	0·00	0·00	0·00	0·00	0·00	0·00
9·2	0·20	0·239	3·40	1·55	0·50	0·30	0·00	0·00	0·00	0·00
9·2	0·24	0·227	4·90	2·00	0·15	0·10	0·00	0·00	0·00	0·00
9·2	0·58	0·235	15·80	5·30	4·80	3·00	1·65	0·00	0·00	0·00
9·2	0·65	0·234	21·50	8·20	7·60	5·50	2·15	1·60	0·00	0·00
9·2	0·85	0·232	49·85	18·20	20·00	10·20	4·40	4·00	1·30	0·40
4·0	0·58	0·116	25·50	6·60	2·95	2·60	0·25	0·25	0·00	0·00
5·5	0·58	0·166	22·00	5·10	3·80	2·70	0·00	0·00	0·00	0·00
6·5	0·58	0·188	22·30	2·00	1·50	0·50	0·00	0·00	0·00	0·00
7·5	0·58	0·204	24·65	6·45	6·00	4·10	0·25	0·00	0·00	0·00
8·5	0·58	0·267	32·65	7·20	8·50	3·20	1·80	0·00	0·25	0·00
5·5	0·58	0·424	*	*	*	6·85	1·00	0·50	0·25	0·50
5·5	0·58	0·370	*	14·85	17·35	2·05	0·00	0·00	0·00	0·00
5·5	0·58	0·313	155·00	16·60	15·30	7·75	2·15	0·50	0·00	0·00
5·5	0·58	0·246	40·40	7·75	8·50	3·85	2·00	0·50	0·00	0·00
5·5	0·58	0·213	30·10	9·35	5·45	1·00	0·70	0·50	0·00	0·00
5·5	0·58	0·192	31·90	6·20	5·90	1·90	1·20	0·00	0·00	0·00
5·5	0·58	0·144	20·25	7·80	4·20	2·70	0·20	0·10	0·00	0·00
5·5	0·58	0·172	21·90	4·80	5·05	1·35	0·00	0·00	0·00	0·00
5·5	0·58	0·124	22·45	5·55	6·60	1·50	1·45	0·25	0·00	0·00
5·5	0·58	0·103	16·35	1·95	3·95	2·20	0·00	0·00	0·00	0·00
5·5	0·58	0·070	9·75	2·60	0·70	0·50	0·00	0·00	0·00	0·00

* more than half of the grains transported out of the flume

RESULTS

Experiment set I

The results of experiment set I are shown in Figures 2 to 7. As Figures 2 to 4 demonstrate, for a given amount of flow energy, median transport distance of the particles increases with rainfall energy. This demonstration is most clear-cut for the experiments conducted on the 3·5° slope. At the higher gradients there is more scatter in the data, though the general pattern is maintained. Thus these experiments show that transport distance of particles depends upon both flow energy and rainfall energy. Some insight into the nature of the dependency of transport distance upon the two sources of applied energy is given by Figures 5 to 7. These diagrams show that for low values of either rainfall energy or flow energy, transport distances are also low. High transport distances are achieved only when high values of rainfall energy are combined with high values of flow energy. Transport distance appears to be a function not simply of the total amount of applied energy, but of the interaction of rainfall and flow energy. The combined effects of the two energy sources on transport distance appears to be multiplicative, rather than additive. Inasmuch as the rainfall and flow energies employed in these experiments encompass the ranges found in most natural interrill overland flow, it might be anticipated that this multiplicative effect of rainfall and flow energies on sediment transport will be found in much of natural interrill flow.

Experiment set II

The purpose of this set of experiments was to provide the data from which a predictive equation for sediment-transport competence could be derived. Accordingly, it is necessary to precede an analysis of the results of these experiments with a definition of sediment-transport competence.

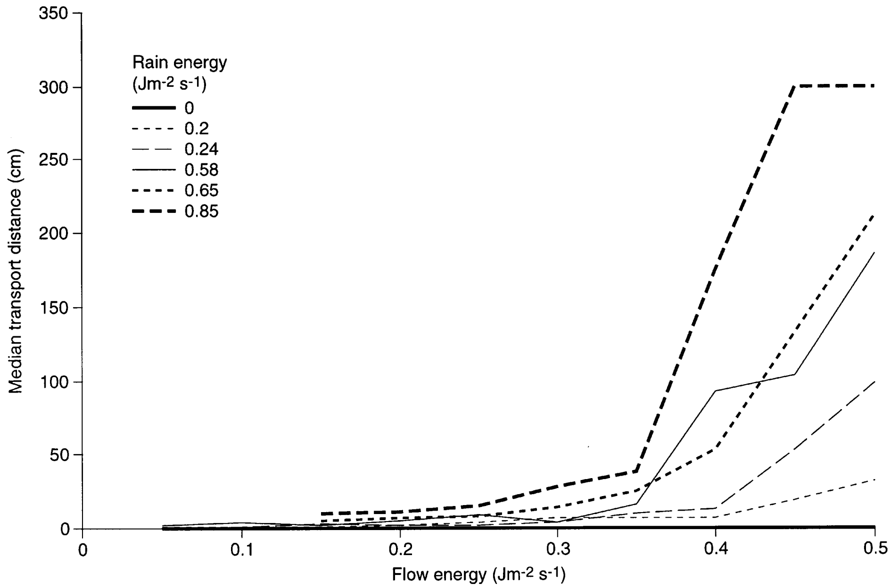

Figure 2. Median transport distances for a 3 mm diameter particle on a 3·5° slope under rainfall energy varying from 0 to 0·85 J m^{-2} s^{-1} and flow energy varying from 0·05 to 0·50 J m^{-2} s^{-1}

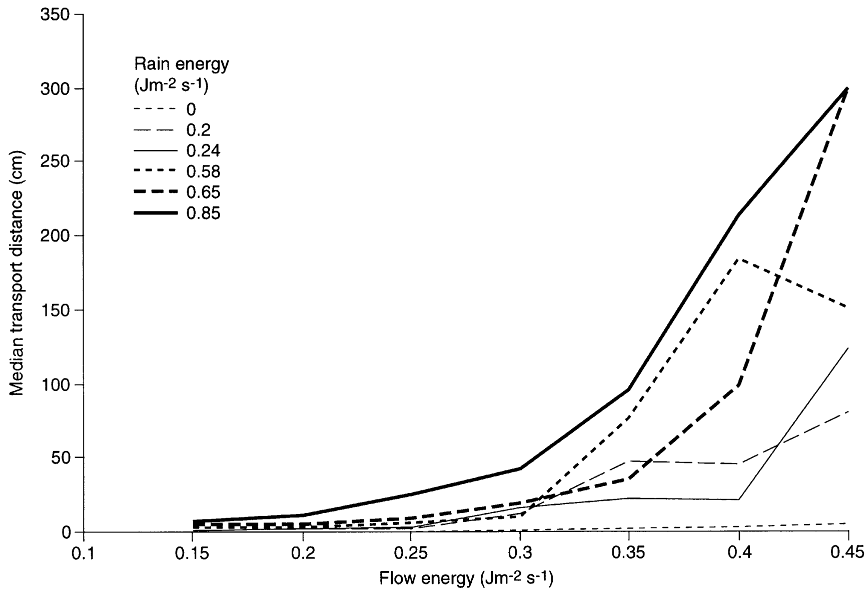

Figure 3. Median transport distances for a 3 mm diameter particle on a 5·5° slope under rainfall energy varying from 0 to 0·85 J m^{-2} s^{-1}

As the results of the first set of experiments show, it is possible to relate the median transport distance of particles of a given size during a known period of time to applied rainfall and flow energy. The results of these experiments would be most useful if it were possible to derive a more general equation of the form:

$$\text{mass times distance} = f\{\text{applied rainfall and flow energy}\} \qquad (2)$$

Using such an equation, it would be possible to predict the median transport distance of particles of a given mass in response to a given input of rainfall and flow energy. The results of the first set of experiments (Figures 2 to 7) suggest that the likely equation will be:

$$ML = k(RE\,FE)^m \qquad (3)$$

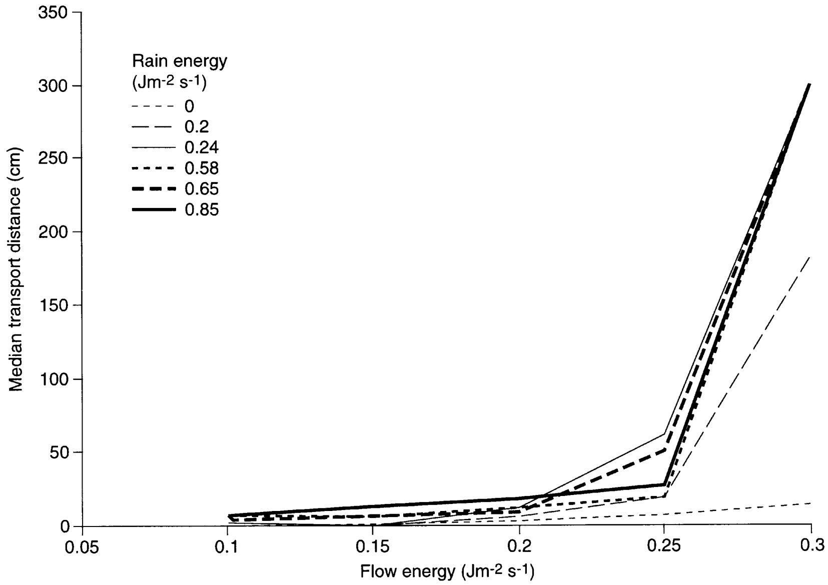

Figure 4. Median transport distances for a 3 mm diameter particle on a 10·0° slope under rainfall energy varying from 0 to 0·85 J m^{-2} s^{-1} and flow energy varying from 0·05 to 0·50 J m^{-2} s^{-1}

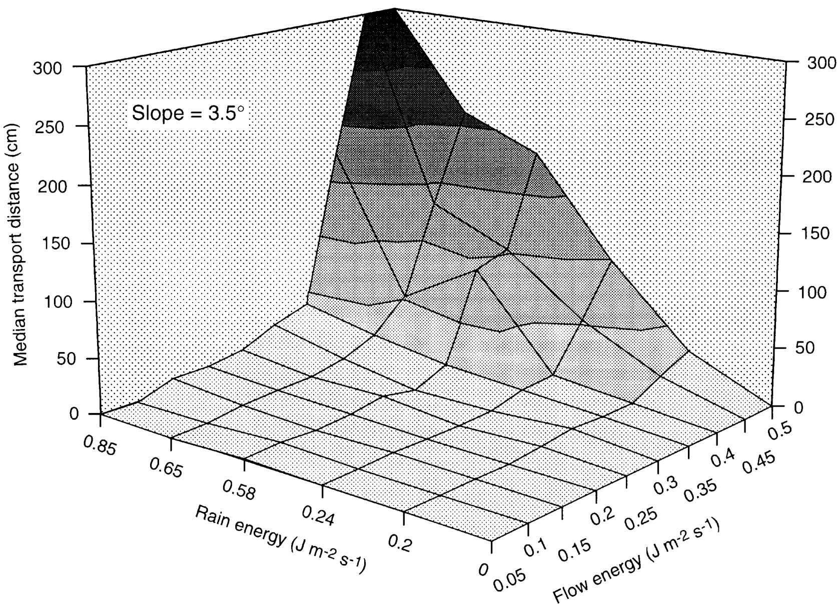

Figure 5. Three-dimensional plot of median transport distances for a 3 mm diameter particle on a 3·5° slope under rainfall energy varying from 0 to 0·85 J m^{-2} s^{-1} and flow energy varying from 0·05 to 0·50 J m^{-2} s^{-1}

in which M is particle mass (g), L is distance moved in unit time (cm min^{-1}), RE is rainfall energy (J m^{-2} s^{-1}), FE is flow energy (J m^{-2} s^{-1}) and k and m are constants.

Taking the measured masses of the particles used in the experiments, the median transport distances obtained from the second set of experiments have been converted to units of mass–distance/unit time and plotted against the product of rainfall energy and flow energy (Figures 8 and 9). These figures show that there is a relationship between sediment mass–distance/unit time and applied energy that is consistent across the range

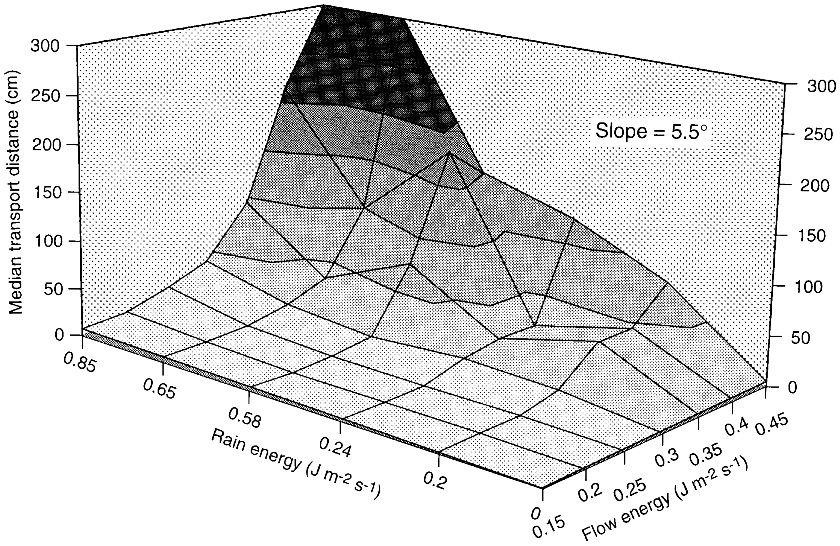

Figure 6. Three dimensional plot of median transport distances for a 3 mm diameter particle on a 5·5° slope under rainfall energy varying from 0 to 0·85 J m^{-2} s^{-1} and flow energy varying from 0·05 to 0·50 J m^{-2} s^{-1}

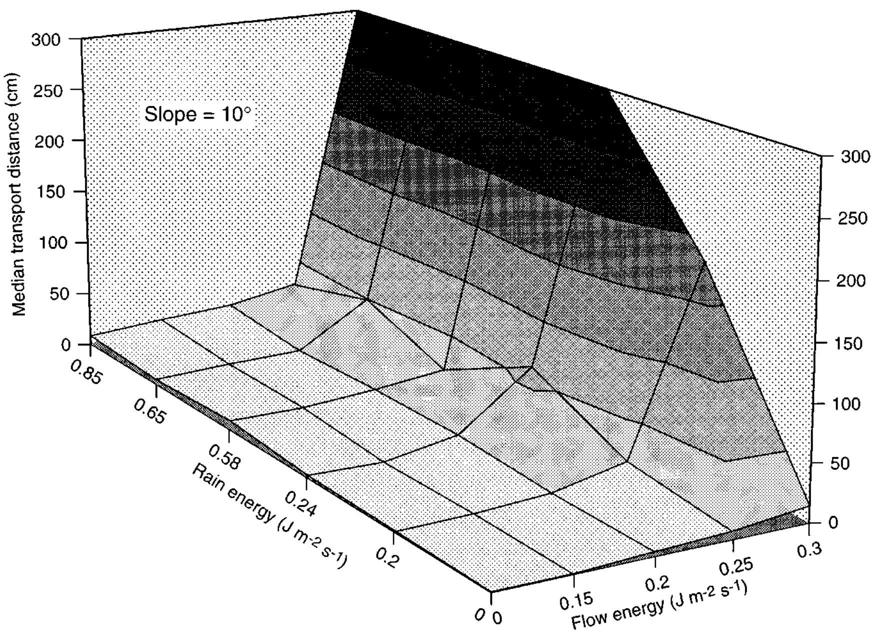

Figure 7. Three dimensional plot of median transport distances for a 3 mm diameter particle on a 10·0° slope under rainfall energy varying from 0 to 0·85 J m^{-2} s^{-1} and flow energy varying from 0·05 to 0·50 J m^{-2} s^{-1}

of particle sizes and gradients used in the experiments. Regression analysis of the data shown in Figures 8 and 9 yields the equation:

$$ML = (RE\ FE)^{1\cdot 6363} \tag{4}$$

for which $r^2 = 0\cdot 53$. (Note that in this equation the constant k turns out to have the value 1.) Using this equation, it is thus possible to predict (within the range of conditions studied) median transport distances for particles of any

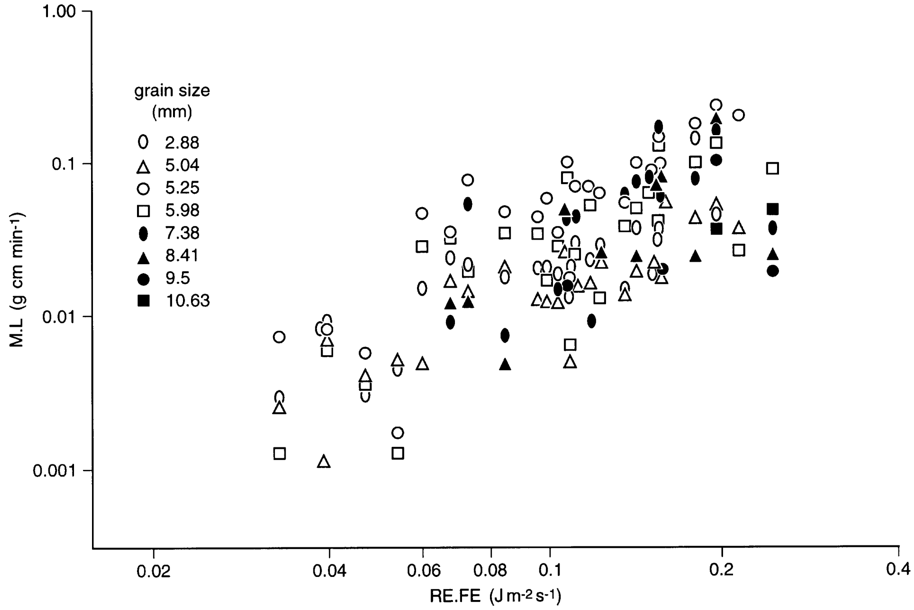

Figure 8. Particle transport (mass–distance/unit time) as a function of the product of rainfall and flow energy. Data are shown sorted by grain size

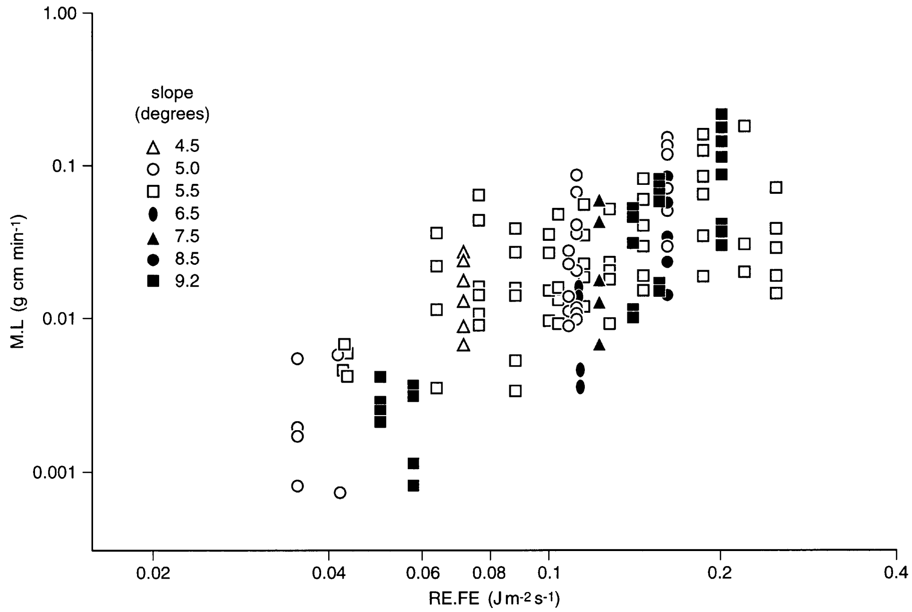

Figure 9. Particle transport (mass–distance/unit time) as a function of the product of rainfall and flow energy. Data are shown sorted by flume gradient

mass under given conditions of rainfall and overland flow.

If an attempt is made to disaggregate the two sources of energy by performing a stepwise multiple regression using rainfall and flow energy as the two independent variables, the following result is obtained:

$$ML = 0{\cdot}525RE^{2{\cdot}35}FE^{0{\cdot}981} \qquad (5)$$

for which $r^2 = 0{\cdot}62$. Rainfall energy is the first variable to enter the equation, explaining 52 per cent of the variance in the dependent variable.

DISCUSSION

The results of the experiments reported above provide the first available means for predicting the size of sediment capable of being transported in rain-impacted interrill overland flow. As such, it is important to recognize the limitations of the predictive equation that are a consequence of the experimental method. These limitations relate to the materials used for the bed of the flume and the transported particles.

The flume bed

The flume bed affects the results of the experiments in two ways. First, the size of material used to create the flume bed defines the surface roughness and, consequently, the mobility of transported particles on the surface. An effect of this surface roughness was noted in the results of experiment set I. In the experiments on the 3·5° slope, transported particles rolled only a short distance in coming to rest on the flume bed. At steeper gradients, the distance of rolling increased, as did its variance. This variable distance of rolling introduced a stochastic element into the transport distances that accounts for the less consistent relationships between transport distance and rainfall and flow energy. Clearly, this effect will be reduced on rougher surfaces. Secondly, the rigid wooden floor of the flume onto which the sand particles were glued absorbed very little of the energy of the falling rain. In consequence, most of the rainfall energy was available for promoting sediment transport. This property of the bed almost certainly contributed to the observed greater importance of rainfall energy in controlling sediment-transport competence (Equation 5). The extent to which natural surfaces are able to absorb rainfall energy, and the effect of such absorption on transport competence and the relative importance of rain and flow energy all need to be investigated.

The transported particles

All the particles used in the experiments were quartz grains (density 2·65 g cm^{-3}). Although these particles are comparable to coarse mineral particles in soils, and thus provide data on the transportability of such particles, they have a much higher density than soil aggregates. The predictive equation may not, therefore, be a reliable predictor of transport competence of soil aggregates of comparable size. Inasmuch as particle size affects sediment detachment by raindrops (Parsons *et al*., 1993) it is unlikely that transport competence for partices of different densities can be predicted simply by incorporating particle density into Equation 3.

CONCLUSIONS

This study has used laboratory experiments to derive an equation for predicting transport competence of shallow, rain-impacted flow. The equation can be used to predict median transport distances for particles ranging from 3 mm to 10 mm diameter under rain with intensities up to 138 mm h^{-1} falling onto flow up to 5 mm deep. It is thus an appropriate equation for predicting transport competence of most interrill overland flow. The equation is limited in its utility insofar as it has been developed using quartz grains and takes no account of variations in absorption of rain energy by natural ground surfaces.

ACKNOWLEDGEMENTS

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